

# First Measurement of the Inclusive Branching Ratio of b Hadrons to $\phi$ Mesons in $Z^0$ Decays

The OPAL Collaboration

## Abstract

The inclusive production rate of  $\phi$  mesons from the decay of b hadrons produced in  $Z^0$  decays was measured to be  $\text{Br}(b \rightarrow \phi X) = 0.0282 \pm 0.0013 \text{ (stat.)} \pm 0.0019 \text{ (syst.)}$ , using data collected by the OPAL detector at LEP.

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# The OPAL Collaboration

G. Abbiendi<sup>2</sup>, K. Ackerstaff<sup>8</sup>, C. Ainsley<sup>5</sup>, P.F. Akesson<sup>3</sup>, G. Alexander<sup>22</sup>, J. Allison<sup>16</sup>, K.J. Anderson<sup>9</sup>, S. Arcelli<sup>17</sup>, S. Asai<sup>23</sup>, S.F. Ashby<sup>1</sup>, D. Axen<sup>27</sup>, G. Azuelos<sup>18,a</sup>, I. Bailey<sup>26</sup>, A.H. Ball<sup>8</sup>, E. Barberio<sup>8</sup>, R.J. Barlow<sup>16</sup>, S. Baumann<sup>3</sup>, T. Behnke<sup>25</sup>, K.W. Bell<sup>20</sup>, G. Bella<sup>22</sup>, A. Bellerive<sup>9</sup>, S. Bentvelsen<sup>8</sup>, S. Bethke<sup>14,i</sup>, O. Biebel<sup>14,i</sup>, I.J. Bloodworth<sup>1</sup>, P. Bock<sup>11</sup>, J. Böhme<sup>14,h</sup>, O. Boeriu<sup>10</sup>, D. Bonacorsi<sup>2</sup>, M. Boutemour<sup>31</sup>, S. Braibant<sup>8</sup>, P. Bright-Thomas<sup>1</sup>, L. Brigliadori<sup>2</sup>, R.M. Brown<sup>20</sup>, H.J. Burckhart<sup>8</sup>, J. Cammin<sup>3</sup>, P. Capiluppi<sup>2</sup>, R.K. Carnegie<sup>6</sup>, A.A. Carter<sup>13</sup>, J.R. Carter<sup>5</sup>, C.Y. Chang<sup>17</sup>, D.G. Charlton<sup>1,b</sup>, C. Ciocca<sup>2</sup>, P.E.L. Clarke<sup>15</sup>, E. Clay<sup>15</sup>, I. Cohen<sup>22</sup>, O.C. Cooke<sup>8</sup>, J. Couchman<sup>15</sup>, C. Couyoumtzelis<sup>13</sup>, R.L. Coxe<sup>9</sup>, M. Cuffiani<sup>2</sup>, S. Dado<sup>21</sup>, G.M. Dallavalle<sup>2</sup>, S. Dallison<sup>16</sup>, A. de Roeck<sup>8</sup>, P. Dervan<sup>15</sup>, K. Desch<sup>25</sup>, B. Dienes<sup>30,h</sup>, M.S. Dixit<sup>7</sup>, M. Donkers<sup>6</sup>, J. Dubbert<sup>31</sup>, E. Duchovni<sup>24</sup>, G. Duckeck<sup>31</sup>, I.P. Duerdoth<sup>16</sup>, P.G. Estabrooks<sup>6</sup>, E. Etzion<sup>22</sup>, F. Fabbri<sup>2</sup>, M. Fanti<sup>2</sup>, L. Feld<sup>10</sup>, P. Ferrari<sup>12</sup>, F. Fiedler<sup>8</sup>, I. Fleck<sup>10</sup>, M. Ford<sup>5</sup>, A. Frey<sup>8</sup>, A. Fürties<sup>8</sup>, D.I. Futyan<sup>16</sup>, P. Gagnon<sup>12</sup>, J.W. Gary<sup>4</sup>, G. Gaycken<sup>25</sup>, C. Geich-Gimbel<sup>3</sup>, G. Giacomelli<sup>2</sup>, P. Giacomelli<sup>8</sup>, D. Glenzinski<sup>9</sup>, J. Goldberg<sup>21</sup>, C. Grandi<sup>2</sup>, K. Graham<sup>26</sup>, E. Gross<sup>24</sup>, J. Grunhaus<sup>22</sup>, M. Gruwe<sup>25</sup>, P.O. Günther<sup>3</sup>, C. Hajdu<sup>29</sup>, G.G. Hanson<sup>12</sup>, M. Hansroul<sup>8</sup>, M. Hapke<sup>13</sup>, K. Harder<sup>25</sup>, A. Harel<sup>21</sup>, C.K. Hargrove<sup>7</sup>, M. Harin-Dirac<sup>4</sup>, A. Hauke<sup>3</sup>, M. Hauschild<sup>8</sup>, C.M. Hawkes<sup>1</sup>, R. Hawkins<sup>25</sup>, R.J. Hemingway<sup>6</sup>, C. Hensel<sup>25</sup>, G. Herten<sup>10</sup>, R.D. Heuer<sup>25</sup>, M.D. Hildreth<sup>8</sup>, J.C. Hill<sup>5</sup>, A. Hocker<sup>9</sup>, K. Hoffman<sup>8</sup>, R.J. Homer<sup>1</sup>, A.K. Honma<sup>8</sup>, D. Horváth<sup>29,c</sup>, K.R. Hossain<sup>28</sup>, R. Howard<sup>27</sup>, P. Hüntemeyer<sup>25</sup>, P. Igo-Kemenes<sup>11</sup>, K. Ishii<sup>23</sup>, F.R. Jacob<sup>20</sup>, A. Jawahery<sup>17</sup>, H. Jeremie<sup>18</sup>, C.R. Jones<sup>5</sup>, P. Jovanovic<sup>1</sup>, T.R. Junk<sup>6</sup>, N. Kanaya<sup>23</sup>, J. Kanzaki<sup>23</sup>, G. Karapetian<sup>18</sup>, D. Karlen<sup>6</sup>, V. Kartvelishvili<sup>16</sup>, K. Kawagoe<sup>23</sup>, T. Kawamoto<sup>23</sup>, R.K. Keeler<sup>26</sup>, R.G. Kellogg<sup>17</sup>, B.W. Kennedy<sup>20</sup>, D.H. Kim<sup>19</sup>, K. Klein<sup>11</sup>, A. Klier<sup>24</sup>, T. Kobayashi<sup>23</sup>, M. Kobel<sup>3</sup>, T.P. Kokott<sup>3</sup>, S. Komamiya<sup>23</sup>, R.V. Kowalewski<sup>26</sup>, T. Kress<sup>4</sup>, P. Krieger<sup>6</sup>, J. von Krogh<sup>11</sup>, T. Kuhl<sup>3</sup>, M. Kupper<sup>24</sup>, P. Kyberd<sup>13</sup>, G.D. Lafferty<sup>16</sup>, H. Landsman<sup>21</sup>, D. Lanske<sup>14</sup>, I. Lawson<sup>26</sup>, J.G. Layter<sup>4</sup>, A. Leins<sup>31</sup>, D. Lellouch<sup>24</sup>, J. Letts<sup>12</sup>, L. Levinson<sup>24</sup>, R. Liebisch<sup>11</sup>, J. Lillich<sup>10</sup>, B. List<sup>8</sup>, C. Littlewood<sup>5</sup>, A.W. Lloyd<sup>1</sup>, S.L. Lloyd<sup>13</sup>, F.K. Loebinger<sup>16</sup>, G.D. Long<sup>26</sup>, M.J. Losty<sup>7</sup>, J. Lu<sup>27</sup>, J. Ludwig<sup>10</sup>, A. Macchiolo<sup>18</sup>, A. Macpherson<sup>28</sup>, W. Mader<sup>3</sup>, M. Mannelli<sup>8</sup>, S. Marcellini<sup>2</sup>, T.E. Marchant<sup>16</sup>, A.J. Martin<sup>13</sup>, J.P. Martin<sup>18</sup>, G. Martinez<sup>17</sup>, T. Mashimo<sup>23</sup>, P. Mättig<sup>24</sup>, W.J. McDonald<sup>28</sup>, J. McKenna<sup>27</sup>, T.J. McMahon<sup>1</sup>, R.A. McPherson<sup>26</sup>, F. Meijers<sup>8</sup>, P. Mendez-Lorenzo<sup>31</sup>, F.S. Merritt<sup>9</sup>, H. Mes<sup>7</sup>, A. Michelini<sup>2</sup>, S. Mihara<sup>23</sup>, G. Mikenberg<sup>24</sup>, D.J. Miller<sup>15</sup>, W. Mohr<sup>10</sup>, A. Montanari<sup>2</sup>, T. Mori<sup>23</sup>, K. Nagai<sup>8</sup>, I. Nakamura<sup>23</sup>, H.A. Neal<sup>12,f</sup>, R. Nisius<sup>8</sup>, S.W. O’Neale<sup>1</sup>, F.G. Oakham<sup>7</sup>, F. Odorici<sup>2</sup>, H.O. Ogren<sup>12</sup>, A. Oh<sup>8</sup>, A. Okpara<sup>11</sup>, M.J. Oreglia<sup>9</sup>, S. Orito<sup>23</sup>, G. Pásztor<sup>8,j</sup>, J.R. Pater<sup>16</sup>, G.N. Patrick<sup>20</sup>, J. Patt<sup>10</sup>, P. Pfeifenschneider<sup>14</sup>, J.E. Pilcher<sup>9</sup>, J. Pinfold<sup>28</sup>, D.E. Plane<sup>8</sup>, B. Poli<sup>2</sup>, J. Polok<sup>8</sup>, O. Pooth<sup>8</sup>, M. Przybycień<sup>8,d</sup>, A. Quadt<sup>8</sup>, C. Rembser<sup>8</sup>, H. Rick<sup>4</sup>, S.A. Robins<sup>21</sup>, N. Rodning<sup>28</sup>, J.M. Roney<sup>26</sup>, S. Rosati<sup>3</sup>, K. Roscoe<sup>16</sup>, A.M. Rossi<sup>2</sup>, Y. Rozen<sup>21</sup>, K. Runge<sup>10</sup>, O. Runolfsson<sup>8</sup>, D.R. Rust<sup>12</sup>, K. Sachs<sup>6</sup>, T. Saeki<sup>23</sup>, O. Sahr<sup>31</sup>, E.K.G. Sarkisyan<sup>22</sup>, C. Sbarra<sup>26</sup>, A.D. Schaile<sup>31</sup>, O. Schaile<sup>31</sup>, P. Scharff-Hansen<sup>8</sup>, S. Schmitt<sup>11</sup>, M. Schröder<sup>8</sup>, M. Schumacher<sup>25</sup>, C. Schwick<sup>8</sup>, W.G. Scott<sup>20</sup>, R. Seuster<sup>14,h</sup>, T.G. Shears<sup>8</sup>, B.C. Shen<sup>4</sup>, C.H. Shepherd-Themistocleous<sup>5</sup>, P. Sherwood<sup>15</sup>, G.P. Siroli<sup>2</sup>, A. Skuja<sup>17</sup>, A.M. Smith<sup>8</sup>, G.A. Snow<sup>17</sup>, R. Sobie<sup>26</sup>, S. Söldner-Rembold<sup>10,e</sup>, S. Spagnolo<sup>20</sup>, M. Sproston<sup>20</sup>, A. Stahl<sup>3</sup>, K. Stephens<sup>16</sup>, K. Stoll<sup>10</sup>, D. Strom<sup>19</sup>, R. Ströhmer<sup>31</sup>, B. Surrow<sup>8</sup>, S.D. Talbot<sup>1</sup>, S. Tarem<sup>21</sup>, R.J. Taylor<sup>15</sup>, R. Teuscher<sup>9</sup>, M. Thiergen<sup>10</sup>, J. Thomas<sup>15</sup>, M.A. Thomson<sup>8</sup>, E. Torrence<sup>9</sup>, S. Towers<sup>6</sup>, T. Trefzger<sup>31</sup>, I. Trigger<sup>8</sup>, Z. Trócsányi<sup>30,g</sup>, E. Tsur<sup>22</sup>, M.F. Turner-Watson<sup>1</sup>, I. Ueda<sup>23</sup>, P. Vannerem<sup>10</sup>,

M. Verzocchi<sup>8</sup>, H. Voss<sup>8</sup>, J. Vossebeld<sup>8</sup>, D. Waller<sup>6</sup>, C.P. Ward<sup>5</sup>, D.R. Ward<sup>5</sup>, P.M. Watkins<sup>1</sup>,  
A.T. Watson<sup>1</sup>, N.K. Watson<sup>1</sup>, P.S. Wells<sup>8</sup>, T. Wengler<sup>8</sup>, N. Wermes<sup>3</sup>, D. Wetterling<sup>11</sup>  
J.S. White<sup>6</sup>, G.W. Wilson<sup>16</sup>, J.A. Wilson<sup>1</sup>, T.R. Wyatt<sup>16</sup>, S. Yamashita<sup>23</sup>, V. Zacek<sup>18</sup>,  
D. Zer-Zion<sup>8</sup>

<sup>1</sup>School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, UK

<sup>2</sup>Dipartimento di Fisica dell' Università di Bologna and INFN, I-40126 Bologna, Italy

<sup>3</sup>Physikalisches Institut, Universität Bonn, D-53115 Bonn, Germany

<sup>4</sup>Department of Physics, University of California, Riverside CA 92521, USA

<sup>5</sup>Cavendish Laboratory, Cambridge CB3 0HE, UK

<sup>6</sup>Ottawa-Carleton Institute for Physics, Department of Physics, Carleton University, Ottawa, Ontario K1S 5B6, Canada

<sup>7</sup>Centre for Research in Particle Physics, Carleton University, Ottawa, Ontario K1S 5B6, Canada

<sup>8</sup>CERN, European Organisation for Nuclear Research, CH-1211 Geneva 23, Switzerland

<sup>9</sup>Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago IL 60637, USA

<sup>10</sup>Fakultät für Physik, Albert Ludwigs Universität, D-79104 Freiburg, Germany

<sup>11</sup>Physikalisches Institut, Universität Heidelberg, D-69120 Heidelberg, Germany

<sup>12</sup>Indiana University, Department of Physics, Swain Hall West 117, Bloomington IN 47405, USA

<sup>13</sup>Queen Mary and Westfield College, University of London, London E1 4NS, UK

<sup>14</sup>Technische Hochschule Aachen, III Physikalisches Institut, Sommerfeldstrasse 26-28, D-52056 Aachen, Germany

<sup>15</sup>University College London, London WC1E 6BT, UK

<sup>16</sup>Department of Physics, Schuster Laboratory, The University, Manchester M13 9PL, UK

<sup>17</sup>Department of Physics, University of Maryland, College Park, MD 20742, USA

<sup>18</sup>Laboratoire de Physique Nucléaire, Université de Montréal, Montréal, Quebec H3C 3J7, Canada

<sup>19</sup>University of Oregon, Department of Physics, Eugene OR 97403, USA

<sup>20</sup>CLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK

<sup>21</sup>Department of Physics, Technion-Israel Institute of Technology, Haifa 32000, Israel

<sup>22</sup>Department of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel

<sup>23</sup>International Centre for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo 113-0033, and Kobe University, Kobe 657-8501, Japan

<sup>24</sup>Particle Physics Department, Weizmann Institute of Science, Rehovot 76100, Israel

<sup>25</sup>Universität Hamburg/DESY, II Institut für Experimental Physik, Notkestrasse 85, D-22607 Hamburg, Germany

<sup>26</sup>University of Victoria, Department of Physics, P O Box 3055, Victoria BC V8W 3P6, Canada

<sup>27</sup>University of British Columbia, Department of Physics, Vancouver BC V6T 1Z1, Canada

<sup>28</sup>University of Alberta, Department of Physics, Edmonton AB T6G 2J1, Canada

<sup>29</sup>Research Institute for Particle and Nuclear Physics, H-1525 Budapest, P O Box 49, Hungary

<sup>30</sup>Institute of Nuclear Research, H-4001 Debrecen, P O Box 51, Hungary

<sup>31</sup>Ludwigs-Maximilians-Universität München, Sektion Physik, Am Coulombwall 1, D-85748 Garching, Germany

<sup>a</sup> and at TRIUMF, Vancouver, Canada V6T 2A3

<sup>b</sup> and Royal Society University Research Fellow

<sup>c</sup> and Institute of Nuclear Research, Debrecen, Hungary

<sup>d</sup> and University of Mining and Metallurgy, Cracow

<sup>e</sup> and Heisenberg Fellow

<sup>f</sup> now at Yale University, Dept of Physics, New Haven, USA

<sup>g</sup> and Department of Experimental Physics, Lajos Kossuth University, Debrecen, Hungary

<sup>h</sup> and MPI München

<sup>i</sup> now at MPI für Physik, 80805 München

<sup>j</sup> and Research Institute for Particle and Nuclear Physics, Budapest, Hungary.

## 1 Introduction

In  $Z^0$  decays,  $\phi$  mesons are produced from three sources: direct production in the fragmentation process, decay of charm hadrons in  $Z^0 \rightarrow c\bar{c}$  events and from the decay of bottom hadrons. According to the spectator model,  $B_u$  and  $B_d$  mesons decay to a  $\phi$  meson via the cascade decay,  $b \rightarrow c \rightarrow \phi$ . Previous measurements of the branching ratio  $\text{Br}(B_u/B_d \rightarrow \phi X)$  were made by the CLEO [1] and ARGUS [2] collaborations and were averaged by the Particle Data Group to give the result  $\text{Br}(B_u/B_d \rightarrow \phi X) = 0.035 \pm 0.007$  [3].

At LEP, where all b hadron species are produced, another mechanism exists where a  $B_s$  meson also decays directly into a  $\phi$  meson. A measurement of the  $\phi$  production rate in inclusive b hadrons, and in particular the  $\phi$  rates of the individual b hadron species, can be used as an input to improve our knowledge of the  $B_s$  oscillation frequency.

In this paper, we describe a measurement of the production rate of  $\phi$  mesons from b hadrons. This includes both direct and cascade b hadron decays.  $\phi$  mesons were identified in their charged kaon decay mode, and those not coming from  $Z^0 \rightarrow b\bar{b}$  events were suppressed by utilizing the relatively long lifetime of the b hadrons.

## 2 Hadronic Event Selection and Simulation

The data used for this analysis were collected by the OPAL detector [4] from  $e^+e^-$  collisions at LEP between 1990 and 1995 running at centre-of-mass energies in the vicinity of the  $Z^0$  peak. Hadronic  $Z^0$  decays were selected using the number of tracks and the visible energy in each event as described in reference [5]. This selection yielded 4.41 million hadronic events.

For optimisation of the selection of events and for some of the studies of systematic uncertainties, we generated 6.5 million 5-flavour hadronic  $Z^0$  decays (referred to as  $q\bar{q}$  Monte Carlo). Monte Carlo events were also used to determine the selection efficiency for signal and background. For determination of signal efficiency, we generated 80,000  $Z^0 \rightarrow b\bar{b}$  events in which at least one of the b hadrons contained a  $\phi$  meson in its decay chain. For background efficiency, we generated 1 million  $Z^0 \rightarrow c\bar{c}$  events.

All these samples were generated with the JETSET 7.4 Monte Carlo program [6] with parameters tuned to the OPAL data [7]. The heavy quark fragmentation was parameterised by the fragmentation function of Peterson *et al.* [8]; all samples were processed with the full OPAL detector simulation package [9] and subjected to the same reconstruction and analysis algorithms as the data.

### 3 Analysis Procedure

In each event, tracks and electromagnetic clusters that were not associated with a track were combined into jets, using the invariant mass algorithm with the E0 recombination scheme and the parameter  $y_{\text{cut}}$  set to 0.04 [10]. The primary vertex of the event was reconstructed using the tracks and the knowledge of the position and spread of the  $e^+e^-$  collision point [11].

We searched for the decay  $\phi \rightarrow K^+K^-$  in the hadronic event sample by combining two tracks to form a  $\phi$  meson candidate. All two track combinations from the same jet with opposite charges were considered. Each of the two tracks was required to have a momentum of at least 2 GeV/c. Due to the small opening angle of the two kaons, this momentum criterion is equivalent to a cut on the  $\phi$  momentum of about 4 GeV/c, which significantly reduces background from fragmentation while only accepting tracks in a momentum range with good separation between kaons and pions using ionisation energy loss ( $dE/dx$ ) information [12]. The  $dE/dx$  for a kaon candidate track was required to be consistent with that expected for a kaon with a probability of more than 10% as defined in [12]. To further reduce the pion background, the probability for a pion hypothesis was required to be less than 10%. These  $dE/dx$  selection criteria retain 51% of  $\phi$  mesons in the momentum range indicated above, while reducing the combinatorial background by 97%. Figure 1 a) shows the momentum distribution of  $\phi$  mesons from fragmentation, b hadron and c hadron decays in generator level simulation. The fragmentation  $\phi$  meson spectrum peaks at low momentum but also has a tail to high momentum above the signal  $\phi$  mesons. We therefore required the momentum of the  $\phi$  mesons to be smaller than 25 GeV/c.

Since at this point, the hadronic data sample consisted mostly of non- $b\bar{b}$  events, we suppressed these events by means of a b-tagging algorithm, based on reconstructed displaced secondary vertices. An artificial neural network with inputs based on decay length significance, vertex multiplicity and invariant mass information [13], was used to select vertices with a high probability of coming from b hadron decays. Events were accepted if at least one of the jets was tagged by the neural network. The b-tagging selection was found to be 68% efficient for the signal, while rejecting 80% of the remaining background.

The two kaon candidate tracks were fitted to a common vertex in three dimensions and the decay distance, the distance from the primary vertex to the reconstructed secondary vertex, was calculated. Figure 1 b) compares the decay distance distribution of  $\phi$  mesons from fragmentation and from b and c decays which passed the above selection criteria. In this plot, negative decay distance represents candidates with a reconstructed secondary vertex in the hemisphere opposite to the candidate's jet. Motivated by this plot, we rejected candidates with a negative decay distance. This selection left 62% of the remaining background events, while keeping 81% of the signal events.

Candidates were accepted if their invariant mass was in the region:  $1.011 \text{ GeV}/c^2 < M_{KK} < 1.027 \text{ GeV}/c^2$ , which corresponds to about two standard deviations of the reconstructed mass distribution around the nominal  $\phi$  mass. Figure 2 a) shows the invariant mass distribution of the  $K^+K^-$  candidates. A total of 4297 candidates were found in the signal mass region.

#### 3.1 Background Estimation

Two of the three sources of  $\phi$  mesons mentioned in section 1 are considered as background, in addition to the non- $\phi$  background where the  $\phi$  candidate is formed from a random combination of tracks not both from a  $\phi$ . To estimate the combinatorial background, we fitted the  $M_{KK}$

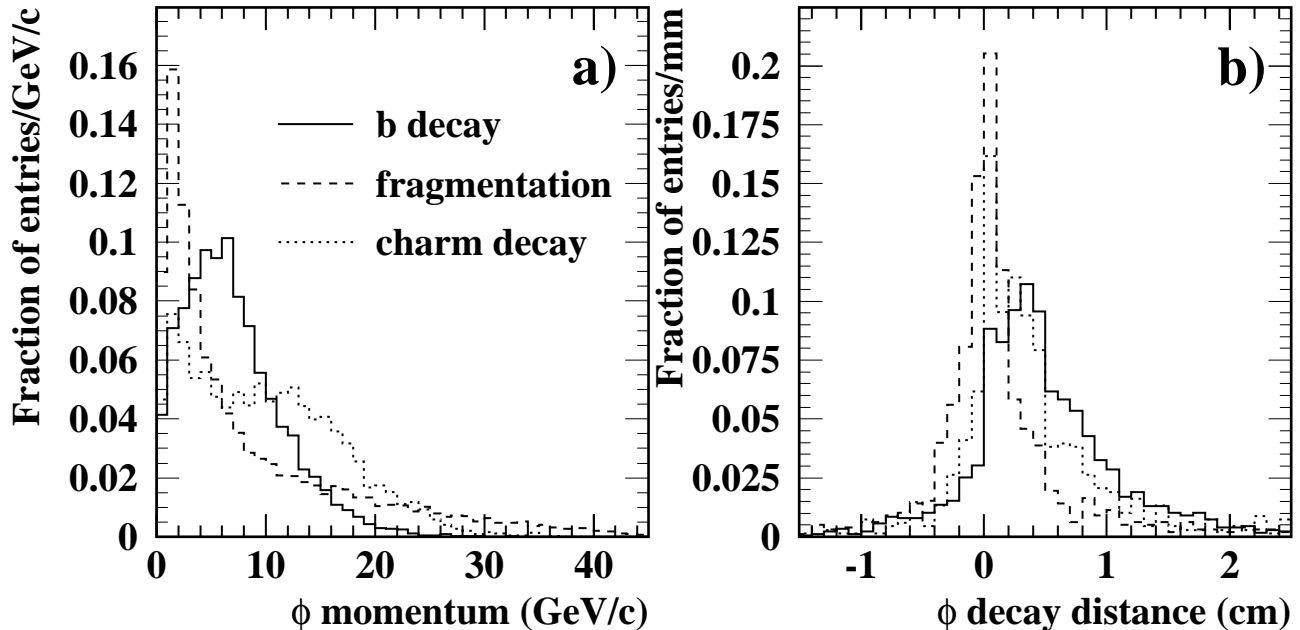


Figure 1: Monte Carlo distributions of (a) true momentum and (b) reconstructed decay distance of  $\phi$  mesons from b decays (solid), fragmentation (dashed) and charm decays (dotted).

distribution to the form

$$f(M_K) = (M_{KK} - 2 \cdot M_K)^a \cdot (b + c \cdot M_{KK} + d \cdot M_{KK}^2), \quad (1)$$

where  $M_K$  is the mass of the charged kaon. The parameters  $a$ ,  $b$ ,  $c$ , and  $d$  were determined from a fit to the combinatorial background in the  $q\bar{q}$  Monte Carlo sample, and then the function shape was normalised to the data in the mass region  $1.060 \text{ GeV}/c^2 < M_{KK} < 1.225 \text{ GeV}/c^2$ . The background shape is superimposed on Figure 2 a). To verify that this technique estimates correctly the background shape, we compared the background-subtracted Monte Carlo sample with the true distribution of Monte Carlo  $\phi$  mesons (figure 2 b). We also compared the background-subtracted  $\phi$  mesons in the data with the true Monte Carlo  $\phi$  distribution (figure 2 c). Both sets of histograms agree with each other very well, thus justifying the procedure for combinatorial background estimation. Subtracting the combinatorial background, we obtained  $2667 \pm 40$   $\phi$  mesons in the signal mass range, where the error arises from the statistical uncertainty on the combinatorial background estimation. The above background estimation ignores a possible small contribution from  $f_0(980)$ . As such a contribution is not well established, we consider it as a systematic uncertainty as described in section 4.1.

The number above contains a small number of  $\phi$  mesons from  $Z^0 \rightarrow c\bar{c}$  decays and from fragmentation. The former was estimated using known and calculated branching ratios of  $D_u$ ,  $D_d$  and  $D_s$  into  $\phi$  mesons, as in [14]. This calculation is based on isospin symmetry ratios

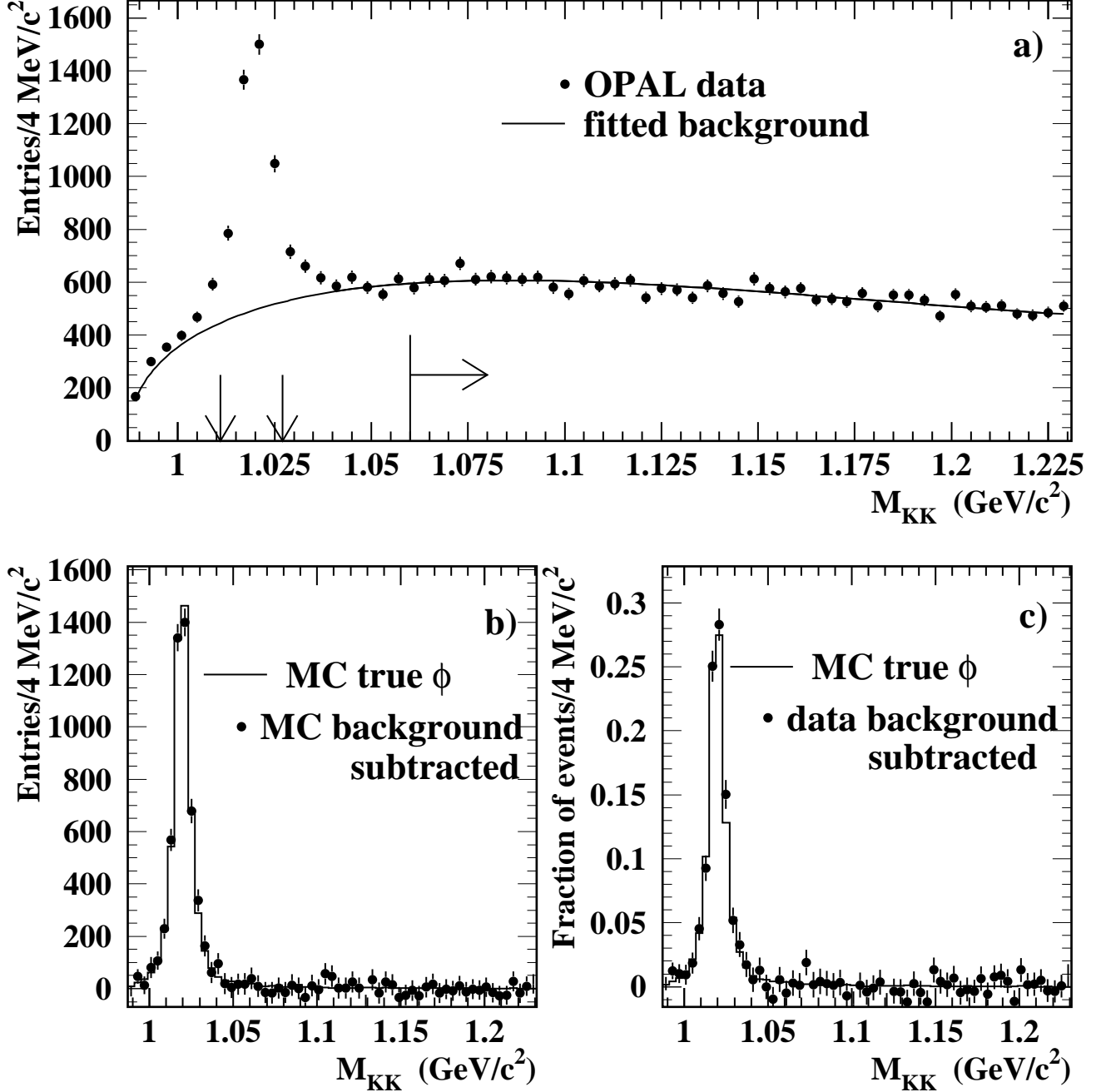


Figure 2: a) Invariant mass distribution of candidates passing all the selection criteria. The solid line represents the combinatorial background estimation as described in the text. The arrows show the signal and fit normalisation regions. b) Comparison of the distribution of true Monte Carlo  $\phi$  mesons with that obtained by subtracting the combinatorial background shape from a fit to the combinatorial background. c) Comparison of the distribution of true Monte Carlo  $\phi$  mesons with that obtained in the data after background-subtraction.

between measured and theoretical branching fractions and was updated to include recent results [3]. We used:

$$\text{Br}(D_u \rightarrow \phi X) = 0.0182 \pm 0.0025, \quad (2)$$

$$\text{Br}(D_d \rightarrow \phi X) = 0.0182 \pm 0.0025, \quad (3)$$

$$\text{Br}(D_s \rightarrow \phi X) = 0.175 \pm 0.025. \quad (4)$$

Using the partial widths of  $Z^0$  into  $c\bar{c}$  and  $f_{D_{u,d,s}}$ , the branching fractions of charm quark into the different D mesons as measured by LEP [15], we estimated the number of  $\phi$  mesons which were produced from charm quarks to be  $52746 \pm 8322$ , where the error includes the uncertainty on all of the above numbers. With an overall efficiency to survive the selection criteria estimated at 1.48% and using  $\text{Br}(\phi \rightarrow K^+K^-) = 0.491 \pm 0.008$  [3], we obtained an estimate of  $389 \pm 61$   $\phi$  mesons from this source. The error, obtained from the above numbers, reflects the systematic uncertainty on this estimation.

The fragmentation  $\phi$  background was estimated directly from the  $q\bar{q}$  Monte Carlo which had been tuned to reproduce the  $\phi$  meson yield in the data [7]. It had also been shown [16], that the shape of the Monte Carlo distribution agrees with that of the data, in particular in the region below 35 GeV. We estimate the number of  $\phi$  mesons from this source to be  $485 \pm 20$ , where the error is from the statistical uncertainty on the Monte Carlo sample used for this estimation.

## 4 Result and Systematic Uncertainties

The number of  $\phi$  mesons which originated from the decay of a b hadron was calculated by subtracting the estimated background contribution from the number of  $\phi$  mesons seen in the data. The result is  $N_\phi = 1793 \pm 50$ , where the error is from the statistical uncertainty on the background level. To calculate the branching fraction, we used:

$$\text{Br}(b \rightarrow \phi X) = \frac{N_\phi}{2 \cdot \Gamma_{b\bar{b}}/\Gamma_{\text{had}} \cdot N_{\text{had}} \cdot \epsilon \cdot \text{Br}(\phi \rightarrow K^+K^-)}, \quad (5)$$

where  $N_{\text{had}}$  is the number of hadronic events and  $\epsilon$  is the selection efficiency for  $\phi$  mesons which originated from b hadron decay. With 4.41 million hadronic events,  $\Gamma_{b\bar{b}}/\Gamma_{\text{had}} = 0.21642 \pm 0.00073$  [15] and  $\epsilon = 0.068 \pm 0.001$ , we obtained

$$\text{Br}(b \rightarrow \phi X) = 0.0282 \pm 0.0013 \pm 0.0019,$$

where the first error is statistical and the second is a 6.6% systematic error, obtained as discussed in detail below.

### 4.1 Systematic Uncertainties

Systematic uncertainties arise from the limited accuracy with which the branching ratios used in this analysis are known, from the uncertainty in the simulation used to determine the efficiency and from the background estimation. All uncertainties quoted below are relative, i.e. with respect to the measured value of  $\text{Br}(b \rightarrow \phi X)$ . Table 1 summarises the systematic uncertainties detailed below.



Systematic Source	$\delta(\text{Br}(b \rightarrow \phi X))/\text{Br}(b \rightarrow \phi X)$ (%)
Branching fractions	3.6
$dE/dx$	3.1
Fragmentation $\phi$	2.8
Heavy quark fragmentation modelling	2.4
Combinatorial background	1.6
Monte Carlo statistics	1.4
$b$ lifetime and decay multiplicity	1.2
Detector modelling	1.2
Total	6.6

Table 1: Systematic uncertainties

### Branching fractions

The uncertainty on the known branching fractions of  $\phi \rightarrow K^+K^-$ ,  $\Gamma_{b\bar{b}}/\Gamma_{\text{had}}$ ,  $\Gamma_{c\bar{c}}/\Gamma_{\text{had}}$ ,  $f_{D_{u,d,s}}$  and  $D_{u,d,s} \rightarrow \phi$  resulted in a 3.6% uncertainty on the branching ratio of  $b \rightarrow \phi X$ . As  $B_s$  mesons also decay directly to  $\phi$  mesons, the efficiency for detecting  $\phi$  mesons from the decay of a  $B_s$  meson is slightly different from that of  $B_{u,d}$ . Since only a small fraction of  $B_s \rightarrow \phi X$  is expected to come from direct decays, we increased the fraction of cascade decays in the Monte Carlo from the current value of 85% to 100%, and recalculated the efficiency. We also varied the production rate of  $b$  hadrons according to the known values [15]. We obtained an additional uncertainty on the efficiency of 0.3%.

### Modelling of $dE/dx$

To estimate the uncertainty arising from the modelling of the  $dE/dx$  selection criteria, we compared the efficiency of the  $dE/dx$  cuts in Monte Carlo events and in data. We reconstructed  $\phi$  mesons without the  $dE/dx$  criteria in data and in Monte Carlo and compared the  $\phi$  yield to that obtained in section 3. We obtained an efficiency associated with the  $dE/dx$  selection criteria of 49.5% in data and 51.0% in Monte Carlo. Hence, the relative uncertainty on the signal efficiency associated with the  $dE/dx$  cuts is estimated at 3.1%. A similar technique was used recently by OPAL [17], and consistent uncertainties obtained.

### Fragmentation $\phi$ mesons

The largest dependence on the Monte Carlo in estimating the background levels is related to fragmentation  $\phi$  mesons. Our selection criteria were designed to reject fragmentation  $\phi$  mesons, thereby limiting the possible uncertainty associated with their simulation. Since we are estimating the fragmentation  $\phi$  background directly from the Monte Carlo, we would like to establish the level of accuracy of the simulation of this source. We took the small difference of  $\phi$  meson yield between the Monte Carlo and the measured value [3], and obtained a relative uncertainty of 2.7%.

A possible shape difference will affect the selection efficiency due to the momentum cuts. We checked the effect of varying the Lund symmetric fragmentation parameters  $a$  (0.11-0.32  $\text{GeV}^{-2}$ ), and  $b$  (0.48-0.58  $\text{GeV}^{-2}$ ). These changes produced a negligible effect. We also varied the parton shower  $\Lambda$  value in the range 0.13 to 0.31  $\text{GeV}$ . This resulted in a relative uncertainty

# OPAL

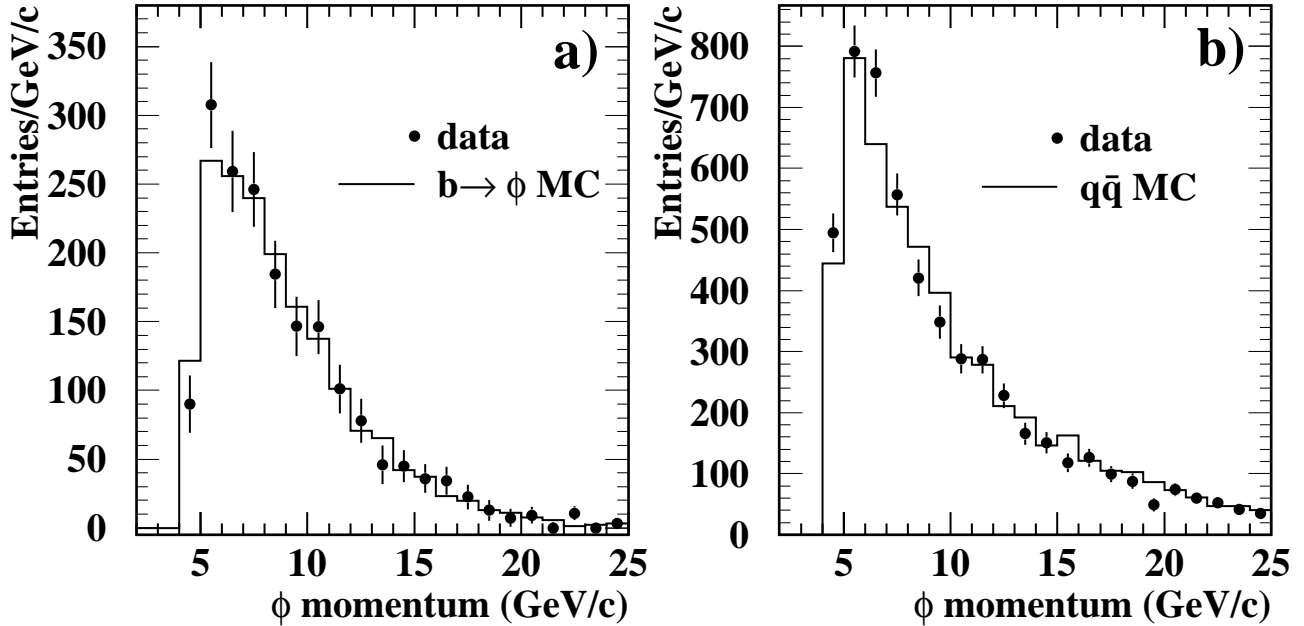


Figure 3: Momentum distributions of (a) data  $\phi$  mesons after background-subtraction (dots) and  $b\bar{b}$  Monte Carlo (histogram), and (b) data and Monte Carlo candidates from events that were rejected by the b-tagger or by the decay distance cut.

on the fragmentation  $\phi$  production rate of 1.6%. We also compared the shape obtained when using the HERWIG event generator [19], and obtained a relative uncertainty of 2.4%. The uncertainty on the production rate of  $\phi$  mesons from the decay of b hadrons associated with the estimation of the fragmentation  $\phi$  background was estimated at 2.8%.

To establish the agreement between the data and the Monte Carlo we show in figure 3 a) the momentum distribution of background-subtracted data and that of simulated  $\phi$  mesons from the decay of b hadrons normalised to the data area. We also compared (figure 3 b) the momentum distribution of  $\phi$  samples which came mostly from fragmentation by selecting events that were rejected by the b-tagger or by the decay distance cut. The data are shown after combinatorial background-subtraction and the Monte Carlo histograms are normalised to the same number of events passing the hadronic event selection. According to the Monte Carlo, 80% of these  $\phi$  mesons are from fragmentation.

## Heavy quark fragmentation modelling

Heavy quark fragmentation was simulated using the function of Peterson *et al.* [8]. The heavy quark fragmentation model parameters were varied to change the mean scaled energy of weakly-decaying bottom and charm hadrons within the experimental range:  $\langle x_E \rangle_b = 0.702 \pm 0.008$  and  $\langle x_E \rangle_c = 0.484 \pm 0.008$  [15]. These changes resulted in a 2.4% relative uncertainty.

## Combinatorial background estimation uncertainty

The uncertainty on the fitted shape parameters and on the normalisation gave an uncertainty on the background estimate. We also repeated the procedure with a function of the form  $f(M_K) = (M_{KK} - 2 \cdot M_K)^a \cdot (b + c \cdot M_{KK})$ , ( $d = 0$  in equation 1). This resulted in 35 additional events or 1.5% relative uncertainty. We also used the Monte Carlo shape directly (without fitting), by normalising the number of combinations in the mass range  $1.06 < M_{KK} < 1.2 \text{ GeV}/c^2$  to that found in the data. With this method, we obtained 1681 events (34 events more than our initial estimate). Since the above two estimates are similar, we took the larger of the two and combined it with the 0.5% of uncertainty from the fitting parameters, to obtain 1.6% uncertainty on the branching ratio associated with the background estimation.

As the contribution from  $f_0(980)$  was neglected in the background estimation, we assigned a conservatively large estimation of this contribution as a systematic uncertainty. We assumed that the width of the  $f_0(980)$  is 100 MeV and that  $\text{Br}(f_0(980) \rightarrow K\bar{K}) = 20\%$ . We used an  $f_0(980)$  multiplicity of 0.14 mesons per hadronic event [3] and obtained the selection efficiency from the Monte Carlo. Combining these numbers, we estimate the contribution of  $f_0(980)$  to the  $K^+K^-$  invariant mass in the signal region to be 6 events. Assuming a 100% uncertainty in this estimate, this translates to 0.3% of relative uncertainty on the branching fraction of  $b \rightarrow \phi X$ .

## b hadron lifetime and decay multiplicity

The probability to reconstruct  $\phi$  mesons from b hadron decays also depends on the efficiency to reconstruct secondary vertices in both hemispheres. This in turn is sensitive to the charged decay multiplicity and lifetime of the b hadrons. The Monte Carlo was reweighted to reflect the measured multiplicities and lifetimes [15]. The uncertainty on these figures gave an uncertainty of 1.2% on the selection efficiency.

## Detector modelling

The simulated resolutions of the tracking detectors were varied by  $\pm 10\%$  relative to the values that optimally describe the data, following the studies in [18]. The analysis was repeated and the efficiencies were estimated again. This source contributed an uncertainty of 1.2%.

# 5 Summary and Discussion

We have searched for direct and cascade decays of b hadrons into  $\phi$  mesons. The  $\phi$  meson was reconstructed in its  $K^+K^-$  decay mode and the fraction of  $Z^0 \rightarrow b\bar{b}$  events in the sample was enriched. We found the branching fraction for this process to be:

$$\text{Br}(b \rightarrow \phi X) = 0.0282 \pm 0.0013 \pm 0.0019.$$

Of special interest is the production rate of  $\phi$  mesons from  $B_s$  mesons. However, as the existing average of  $B^{\pm/0} \rightarrow \phi X$  measurements has 20% uncertainty, it is impossible to obtain a meaningful result for  $\text{Br}(B_s \rightarrow \phi X)$ . On the other hand, our result may be used to obtain an upper limit on the branching ratio of  $B^{\pm/0} \rightarrow \phi X$ . We considered the extreme scenario in which  $B_s$  mesons decay to  $\phi$  mesons only via  $D_s$  decays and used  $\text{Br}(B_s \rightarrow D_s X) = (90 \pm 33)\%$  [3]. We made a conservative assumption that b baryons do not contribute to the  $\phi$  production rate and obtained an upper limit of:  $\text{Br}(B^{\pm/0} \rightarrow \phi X) \leq 0.0285$  at the 90% confidence level. This limit

is consistent with the CLEO result ( $0.023 \pm 0.006 \pm 0.005$ ) [1], but is only marginally consistent with that of ARGUS ( $0.0390 \pm 0.0030 \pm 0.0035$ ) [2].

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